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Isotopic Characterization of Snow Variability in Two Mountainous Catchments, Black Forest Mountains, Germany

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Abstract—**Intense snow sampling was carried out during 2003 and 2004 in two meso-scale catchments (Dreisam catchment, 257 km², and Bergsee catchment, 11 km²) located in the southern Black Forest Mountains in Germany. The objective of the study was to describe the spatial variability of snow cover, snow water equivalent and isotope concentrations of deuterium (^{2}H) and oxygen-18 (^{18}O) in ‰ vs. VSMOW. Snow samples were collected with integral augers and characterized by geographical location, altitude, snow depths and snow characteristics. The results indicate a clear correlation of snow depth and water equivalent with altitude and a rather weak correlation of isotope concentrations to altitude. The isotope concentrations of 65 snow samples collected in 2003 varied between -10.2‰ and -14.9‰ for δ^{18}O, -60‰ and -109‰ for δ^2H and between 10‰ and 25‰ for the deuterium excess (DE). In 2004 the variations of 64 samples were between -7.7‰ and -13.1‰, -43‰ and -87‰ and 4‰ and 28‰, for δ^{18}O, δ^2H and DE respectively. A spatial variability could be described for both catchments. The influence of evaporation of some samples on lower altitudes could be identified using deuterium excess calculations. Our study lead to a better description of isotope variations in snow cover of mountainous catchments and might therefore be useful to enhance tracer aided hydrological modeling approaches which often only refer to precipitation input concentrations of single observation points in monthly resolution.**

Keywords—snow hydrology, stable isotopes, oxygen-18, deuterium, spatial variability, altitude effect, snow cover

I. INTRODUCTION

The study sites are located in the mountainous part of the southern Black Forest Mountains in Germany (Fig. 1). The Dreisam catchment (257 km^2) spans an altitudinal range from 308 m a.m.s.l. at the outlet to 1493 m a.m.s.l. at the summit of the Feldberg. The mean altitude is 780 m a.m.s.l. The basin is widely forested (57%); 40% is pasture land and urban land use is less than 3% (Fig. 1). The climate is generally influenced by the west wind circulation superposed by numerous local effects. Annual precipitation is ~1500 mm a^{-1}, causing a mean annual discharge of ~770 mm a^{-1}. Glacial morphology is evident in landforms such as moraines, cirques, and the U shaped valleys. The study area is underlain by different metamorphic and intrusive rocks and the bedrock material is covered by brown soils developed in the glacial and periglacial drift covers. See [10] for a detailed description of the basin.

The Bergsee catchment (11 km^2) ranges from 380 m a.m.s.l to 1050 m a.m.s.l. (Fig. 1). The mean altitude is about 800 m a.m.s.l. This catchment is less forested (45%) and the urban land use is doubled (6.3%) compared with the Dreisam catchment. Precipitation is comparable to the Dreisam catchment with 1400-1800 mm a^{-1}, whereas annual discharge is about 1000 mm a^{-1}.

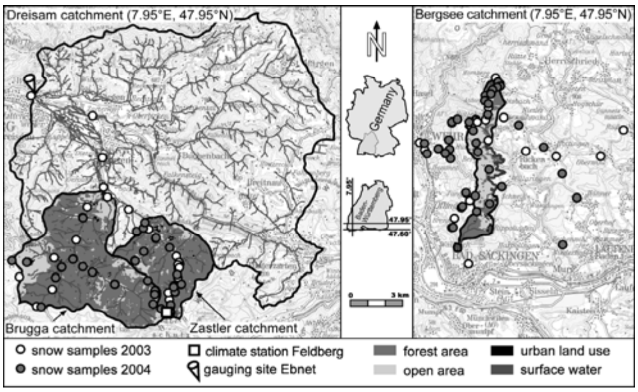

Figure 1. Dreisam catchment (left) and Bergsee catchment (right) including sampling locations for 2003 and 2004.

Snow and therefore snowmelt can be a very important contribution to runoff in snow dominated mountainous catchments, especially at high elevations in the Black Forest Mountains where snow is the dominant input during the winter season. During the melting period in spring snowmelt is an important component of the runoff formation process. Due to the complexity of snow cover and snow melting dynamics and their high spatial and temporal variability it is challenging to include these processes in hydrological models.

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Environmental isotopes like deuterium and oxygen-18 have been used in many studies in the past to investigate processes of snow deposition and changes within the snow cover. For catchment studies it is important to consider the temporal variations of isotopes in the snow cover as an input in the system [e.g. 3, 4, 8, 9, and 11]. Several hydrograph separation studies using isotopes in snowmelt have been carried out in the last decades [e.g. 1, 4, 5, 6, and 7].

The objectives of this study were to (i) characterize the spatial variability of snow cover depths (S_D) and snow water equivalent (S_{WE}) within a snow layer, to (ii) characterize the spatial isotope variability, and to (iii) to test and estimate if there is an isotope altitude effect in snow similar to precipitation studies.

II. Data Collection

A. Snow sampling

Snow samples were taken during four days (02/09/2003, 02/11/2003, 02/10/2004 and 02/18/2004) in two field campaigns in winter 2002/2003 and 2003/2004. At each sampling point the geographical location and altitude was estimated using geographical positioning system (GPS). Snow depths where determined with snow augers and snow characteristics were described. Bulk samples were taken with a snow auger and stored in sealed plastic bags to estimate density of the snow cover and for measurement of the isotopic composition of the melted snow. At certain locations snow profiles were collected in a vertical resolution of 5 to 10 cm steps to describe the vertical distribution of the stabile isotopes in the snow profile. Snow density was determined gravimetrically after melting of the snow sample in the laboratory over night.

B. Isotope Analysis

Oxygen-18 and deuterium values of water samples were analyzed at the Institute of Hydrology at Freiburg University using a Finnigan MAT Delta S dual inlet Isotope Ratio Mass Spectrometer (IRMS). Oxygen-18 was analyzed after 11 hours (20°C) CO_2 equilibration with 5 ml sample aliquot with an equilibration unit. For deuterium analysis 1 µl sample was injected into an H/Device using a chrome reduction method at 900°C. Analytical precision was better than ±0.2‰ and ±1‰ for $\delta^{18}O$ and δ^2H, respectively. Isotope values are expressed in δ-notation in ‰ relative to the international standard VSMOW (Vienna Standard Mean Ocean Water).

III. Results

The meteorological and hydrological conditions during the winter periods 2002/2003 and 2003/2004 were presented in Fig. 2. Daily values of precipitation, air temperature, snow cover and runoff are presented for the period from 1 November to 31 May for the years 2003 and 2004 respectively. Total precipitation of 979 mm and 574 mm was recorded for the investigation periods in 2002/2003 and 2003/2004 respectively. This is 64% and 41% of the total precipitation in the hydrological years (1 November to 31 October). Snow cover depths (S_D) and daily mean air temperature values are closely link with each other. Maximum snow cover depth is 105 cm in 2002/2003 and 96 cm in 2003/2004. Snow cover period ends earlier in 2003 (04/16/03) caused by an extreme temperature increase, compared with the next year where snow cover period extended until mid May (05/17/04). For the period of the current study runoff at gauging site Ebnet show the typical fluctuations due to snow deposition and ablation periods in the catchment. Runoff peaks are mainly related to rainfall and snowmelt events except for the first discharge event in November 2002 which is mainly caused by precipitation input.

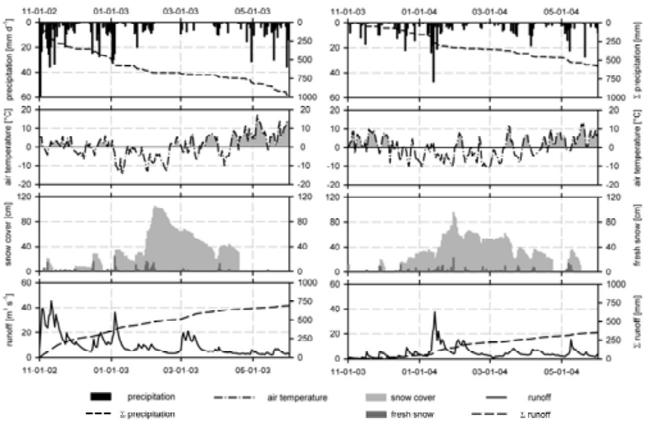

Figure 2. Precipitation, air temperature, snow depths at the climate station Feldberg as well as runoff at gauging site Ebnet (Dreisam river) of the winter periods 2002/2003 and 2003/2004.

Results of the spatial distributed snow measurements show a good correlation between snow depth (S_D) and altitude. The correlation coefficients of the Dreisam basin (Fig. 3) in 2003 and 2004 are r=0.91 and 0.78, respectively.

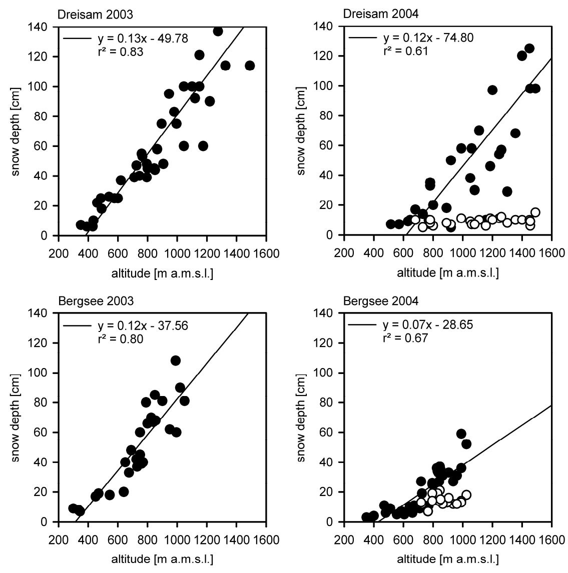

Figure 3. Spatial variability of snow depths on altitude for 2003 and 2004 for Dreisam (top) and Bergsee (bottom). (open symbols represent the upper fresh snow layer only).

At higher positions, above 1000 m a.m.s.l the values have a higher variability in the Dreisam basin. The gradients of the correlations are in the same order of magnitude and show an increase of snow of approximately 12-13 cm per 100 m. In the Bergsee basin there are correlation coefficients of r=0.89 and 0.82, respectively (Fig. 3). The gradients differ for 2003 (12 cm per 100 m) and 2004 (7 cm per 100 m). The thickness of the 2004 fresh fallen snow layer (Fig. 3) is more homogeneous and varies between 5 and 15 cm without a dependence on altitude. The high variability of snow depth at higher altitudes (above 1000 m a.m.s.l.) in the Dreisam basin could be explained by a shift of snow due to strong winds from the round end peaks into the valleys, similar to the varying water contents.

Looking at the stored amount of water in the snow layer, the snow water equivalent (S_{WE}), correlations are less distinctive. The increase of water content with altitude is in the range of 2 mm per 100 m in the Dreisam basin in 2003 and 4 mm for 2004, and in the Bergsee basin 3 mm per 100 m in 2003 and 2 mm in 2004, respectively. There is also, comparable to the snow cover depth, no good correlation with altitude for the fresh fallen snow depth. Total snow depth of this layer range for the Dreisam basin between 5 and 15 cm and for the Bergsee basin between 7 and 21 cm. Similar to snow cover observations the values for water content show a higher variability above 1000 m a.m.s.l.

The $\delta^{18}O$ versus $\delta^{2}H$ isotope values of snow and precipitation samples are plotted in Fig. 4 and compared with to the Global Meteoric Water Line (GMWL) and a Local Meteoric Water Line (LMWL) from Weil am Rhine, a close by station from the Global Network of Isotopes in Precipitation; GNIP database [2]. The means and standard deviations of the values can be found in Tab. 1.

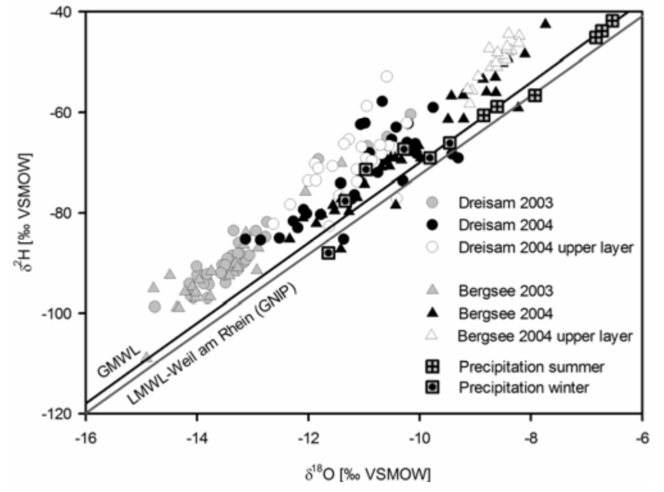

Figure 4. Stable isotope composition of snow samples collected during the snow campaigns in 2002/2003 and 2003/2004 and mean monthly isotope values of precipitation in the Dreisam catchment (1996-2006).

Isotope values of precipitation were collected on a weekly basis at one station inside the Dreisam catchment of the period 1996 to 2006. The long term monthly precipitation amount weighted values are shown in Fig. 4 for summer and winter periods. Mean monthly values for the winter have lighter isotope values compared with summer precipitation values and are in the range of the snow isotope values of 2004. However the snow isotopic samples of 2003 are much lighter than the mean monthly precipitation values during the winter time.

TABLE I. ISOTOPE CONCENTRATIONS (OXYGEN-18 AND DEUTERIUM) AND DEUTERIUM EXCESS MEASURED IN SNOW INTEGRAL SAMPLES IN THE DREISAM AND BERGSEE CATCHMENT AND VALUES FOR PRECIPITATION (1996-2006) AND RUNOFF AT GAUGE EBNET (1999-2006).

Date	*No.*	*Mean +/- SD (‰ VSMOW)*	*Max (‰ VSMOW)*	*Min (‰ VSMOW)*
Oxygen-18				
Snow Dreisam 2003	38	-13.26 +/- 0.95	-10.16	-14.76
Snow Dreisam 2004	52	-11.13 +/- 0.85	-9.31	-13.13
Snow Bergsee 2003	27	-13.46 +/- 0.98	-10.84	-14.91
Snow Bergsee 2004	35	-10.10 +/- 1.32	-7.74	-12.34
Precip. (1996-2006)	132	-9.08 +/- 1.81	-6.54	-11.64
Runoff (1999-2006)	96	-9.28 +/- 0.30	-8.57	-10.07
Deuterium				
Snow Dreisam 2003	35	-87.9 +/- 9.2	-60.4	-98.8
Snow Dreisam 2004	53	-71.4 +/- 7.8	-52.8	-85.5
Snow Bergsee 2003	23	-92.0 +/- 7.9	-70.1	-109.0
Snow Bergsee 2004	34	-66.6 +/- 12.4	-42.6	-87.3
Precip. (1996-2006)	132	-62.21+/- 14.04	-41.81	-88.03
Deuterium excess				
Snow Dreisam 2003	35	18 +/- 3	25	13
Snow Dreisam 2004	52	18 +/- 6	32	5
Snow Bergsee 2003	23	17 +/- 3	23	10
Snow Bergsee 2004	34	14 +/- 4	20	4
Precip. (1996-2006)	132	10 +/- 3	16	5

In Fig. 5 $\delta^{18}O$, $\delta^{2}H$ and deuterium excess values (DE) of integrated and upper layer snow samples are plotted against altitude.

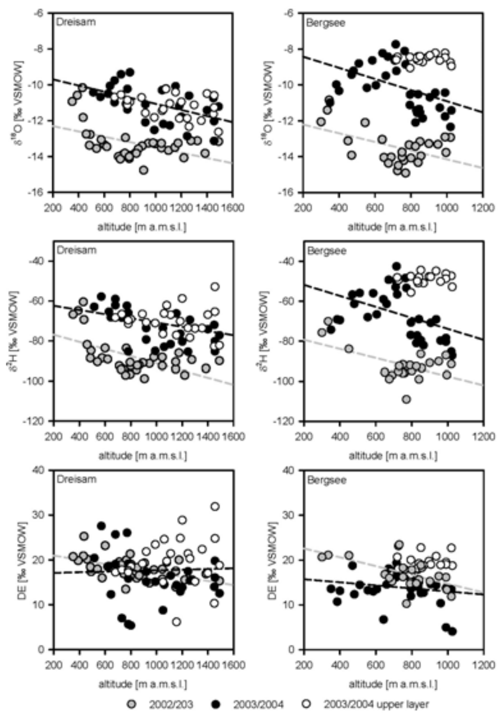

Figure 5. Spatial variability of isotope concentrations and deuterium excess of snow samples for Dreisam (left) and Bergsee (right).

Correlation coefficients are less strong than for snow depths and snow water equivalent investigations and range from r=0.42 to 0.51 for $\delta^{18}O$ and from r=0.41 to 0.57 for $\delta^{2}H$, respectively, over the two sampling periods. However no clear correlations between deuterium excess values and altitude could be observed.

Conclusions

Strong correlations between total snow depth, snow water equivalent and altitude was found in both catchments for the two sampling periods. Also clear relationships were found between stable isotope concentrations of oxygen-18 and deuterium and altitude of the sampling points. Contrary to our conception no significant correlations could be found between deuterium excess values and altitude.

We suggest extending experimental research using environmental isotopes in snow cover investigations, because they can provide useful information to improve our knowledge about runoff processes and runoff components especially during times of ablation and for events caused by snowmelt in mountainous catchments.

Acknowledgment

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References

[1] Dinçer T, Payne BR, Florkowski T, Marinec J, Tongiorgi T. 1970. Snowmelt runoff from measurements of tritium and oxygen-18. *Water Resources Research* **6**: 110-118

[2] IAEA/WMO 2006. Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: http://www.iaea.org/water.

[3] Koeniger P, Hubbart JA, Link T, Marshall JD. (2008): Isotopic variation of snow cover and streamflow in response to changes in canopy structure in a snow-dominated mountain catchment. *Hydrological Processes* **22**: 557-566.

[4] Laudon H, Hemond HF, Krouse R, Bishop KH. 2002. Oxygen-18 fractionation during snowmelt: implications for spring flood hydrograph separation. *Water Resources Research* **38(**11): doi:10.1029/2002WR001510,2002.

[5] Rodhe A. 1987. *The origin of stream water traced by oxygen-18*. Diss. Dept. Earth Sci., Hydrol., Uppsala Univ., Uppsala, Sweden, 333 pp.

[6] Rodhe A. 1998. Snowmelt-Dominated Systems. In: *Isotopes in Catchment Hydrology* (Eds. Kendall, C., Mc Donnell, J.J.). Elsvier / Amsterdam: 391-434.

[7] Sklash, M. G. (1990). Environmental isotope studies of storm and snowmelt runoff generation. In: *Processes in Hillslope Hydrology*. M. G. Anderson and T. P. Burt. Chichester, England, John Wiley & Sons: 401-435.

[8] Taylor S, Feng X, Kirchner JW, Osterhuber R, Klaue B, Renshaw CE. 2001. Isotopic evolution of a seasonal snowpack and its melt. *Water Resources Research* **37**(3): 759-769.

[9] Taylor S, Feng X, Williams M, McNamara J. 2002. How isotopic fractionation of snowmelt affects hydrograph separation. *Hydrological Processes* **16**: 3683-3690.

[10] Uhlenbrook, S. 1999. *Untersuchung und Modellierung der Abflußbildung in einem mesoskaligen Einzugsgebiet.* Freiburger Schriften zur Hydrologie, **10**, University of Freiburg: Freiburg, Germany.

[11] Unnikrishna PV, McDonnell JJ, Kendall C. 2002. Isotope variations in a Sierra Nevada snowpack and their relation to meltwater. *Journal of Hydrology* **260**: 38-57.